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Relationship between elevated plantar pressure of toes and forefoot and gait features in diabetic patients

Ayumi Amemiya[1], Hiroshi Noguchi[2], Makoto Oe[3], Kimie Takehara[1], Amika Yamada[1], Yumiko Ohashi[4], Kohjiro Ueki[5], Takashi Kadowaki[5], Taketoshi Mori[2] and Hiromi Sanada[1]

Abstract— **This cross-sectional observational study is to reveal what kind of gait feature is relevant to elevated segment and its plantar pressure for prevention of diabetic foot ulcers. In 57 diabetic patients, the relationship between elevated plantar pressure and gait features was analyzed. To conduct this investigation, a simultaneous measurement system of plantar pressure and gait features was constructed. Plantar pressure distribution was measured by F-scan with customized footwear, and gait features were mainly measured using wireless motion sensors attached to the sacrum and feet. Several gait features of small rolling during the mid-stance phase were relevant to the elevated plantar pressure.**

I. Introduction

The International Diabetes Federation warns that one person in ten will have diabetes by 2030 [1]. Diabetic foot ulcer is one of the most serious complications of diabetes. Diabetic foot ulcer is a critical problem with a lifetime prevalence of 15%–25% in the diabetic population [2].

The foot ulcers seriously affect quality of life (QOL), reducing physical activity and increasing psychological stress [3]. A 2004 study estimated that diabetic ulcer-related costs averaged over $13,000 per episode, not counting the associated psychosocial, QOL and lost productivity costs [4]. Therefore, prevention of diabetic foot ulcer may improve the QOL and prognosis in diabetic patients. In addition, the social and economic impact of this disorder may be reduced.

High plantar pressure has been identified as a major risk factor for diabetic foot ulcer [5,6]. Avoidance of high plantar pressure may aid in prevention of foot ulcers. Mean peak pressure (MPP) and pressure–time integral (PTI) in the plantar have been demonstrated as risk factors for foot ulcer. PTI represents the amount of force or pressure that is applied over the duration of foot contact. The plantar is generally divided into the four segments in analysis of plantar pressure distribution [7]. A previous study showed a larger number of occurrences of diabetic foot ulcer at the forefoot and toes than at the other segments of the plantar [8]. This study focuses on the plantar pressure of the toes and forefoot.

High plantar pressure is the last step in a process in which several factors contribute in the development of diabetic foot ulcer. Gait alteration is considered one of the major factors. Foot ulcer may be caused by the forces generated during gait [9]. Alterations in gait have been reported in diabetic patients. However, it is not revealed what kind of gait feature is relevant to high plantar pressure. Gait is defined as a person's manner of walking or running. In this study, we investigated gait features by dealing amplitude of motion. Different plantar segments reflect different phases of the gait cycle. The gait cycle has two basic phases: the stance phase and the swing phase. Plantar pressure is relevant to the stance phase in which the limb is in contact with the ground. This phase can be subdivided into three sub-phases: heel-strike, mid-stance and push-off. In general, forefoot segment reflects plantar pressure in the mid-stance phase, while toes segments reflect plantar pressure in the push-off phase. Although gait features and plantar pressure have been simultaneously measured in a few study, their relationship has only been partially inquired. Reduced active ankle range of motion (ROM) and dynamic ankle flexion in the heel-strike phase and reduced amplitude of ROM (flexion–extension) have been found in the subjects with diabetic neuropathy when compared with the nondiabetic subjects. High MPP and PTI are common in the forefoot during the push-off phase, indicating overload in the high-risk segment of the plantar in comparison to the nondiabetic subjects [10]. Research has shown a negative relationship between sagittal motion of the first metatarsal and forefoot and frontal motion of the calcaneus to the PTI in the diabetic patients [11]. However, the association between elevated plantar pressure and gait features has not been examined.

Therefore, the purpose of this study is to reveal what kind of gait feature is relevant to pressure-elevated segment especially at toes and forefoot in the diabetic patients.

II. Methods

A. Subjects and Setting

This cross-sectional observational study was conducted at Diabetic Foot Outpatient Clinic at the University of Tokyo Hospital, from April to October 2012. All diabetic patients who visited this outpatient clinic were recruited. The non-diabetic subjects of matched age and sex were volunteers selected by the snowball sampling method. Subjects who could not walk without aid, those with a current diabetic foot ulcer, those with a history of lower extremity orthopaedic problems, those who could not provide consent for participation, or those who had difficulty in wearing the measurement footwear (foot length >26.5 cm) were excluded

[1]A. Amemiya, K. Takehara, A. Yamada and H. Sanada are with Department of Gerontological Nursing/Wound Care Management, The University of Tokyo 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033 JAPAN (e-mail: aamemiya-tky at umin.ac.jp).
[2]H. Noguchi and T. Mori are with Department of Life Support Technology (Molten), The University of Tokyo 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033 JAPAN.
[3]M. Oe is with Department of Advanced Nursing Technology, The University of Tokyo 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033 JAPAN.
[4]Y. Ohashi is with Department of Nursing, The University of Tokyo Hospital 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033 JAPAN.
[5]K. Ueki and T. Kadowaki are with Department of Diabetes and Metabolic Diseases, The University of Tokyo 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033 JAPAN.

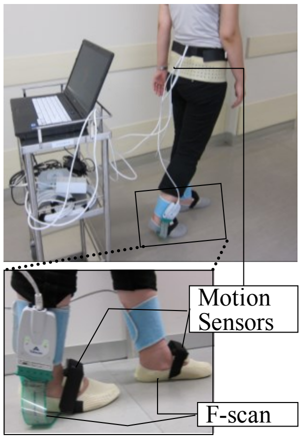

Figure 1.
Measurement system

TABLE 1. Gait Features Classification

Ⅰ Heel-Strike		
	Body Motion Sensor:	Vertical Accel, Pitch AngVelo (ML Axis), Pitch Angle (ML Axis)
	Feet Motion Sensor:	AP Accel, ML Accel, Vertical Accel
Ⅱ Mid-Stance		
	Body Motion Sensor:	AP Accel, Roll AngVelo (AP Axis), Yaw AngVelo (Vertical Axis), Roll Angle (AP Axis), Yaw Angle (Vertical Axis)
	Feet Motion Sensor:	Roll (Inversion) AngVelo (AP Axis), Roll (Inversion) Angle (AP Axis)
	Plantar Pressure Sensor:	COP Excursion Width (ML Axis) (Adjusted or not by Foot Width), Forefoot COP Excursion Width (ML Axis) (Adjusted or not by Foot Width)
Ⅲ Push-Off		
	Feet Motion Sensor:	Roll (Eversion) AngVelo (AP Axis), Pitch AngVelo (ML Axis), Yaw AngVelo (Vertical Axis), Roll (Eversion) Angle (AP Axis), Pitch Angle (ML Axis), Yaw Angle (Vertical Axis)
	Plantar Pressure Sensor:	COP Excursion Length (AP Axis) (Adjusted or not by Foot Length)

Accel: Acceleration, AngVelo: Angular Velocity, AP: Anterior-Posterior, ML: Medio-Lateral

from the study. The study protocol was approved by the Ethical Committee of the Graduate School of Medicine, the University of Tokyo (#3694).

B. Measurement System

Plantar pressure distribution and gait features were measured simultaneously, as shown in Figure 1. Plantar pressure was measured using the F-scan (NITTA CORPORATION, Osaka, Japan) inserted into a pair of customized footwear. Gait was measured by wireless motion sensors (LOGICAL PRODUCT CORPORATION, Fukuoka, Japan) that were attached to the sacrum and dorsal portion of the feet. The motion sensors output three–dimensional acceleration (Accel) and angular velocity (AngVelo) data at these points. Anterior–posterior (AP), medio–lateral (ML) and vertical Accel axes were utilized in this study. Roll, Pitch and Yaw were evaluated on the AngVelo axes (Figure 2). Angles were calculated by integrating AngVelo values after band-pass filtering (0.5–20 Hz). All data were recorded at 200 Hz. The footwear was modified to maintain almost barefoot condition to avoid the influence of confounding factors such as outsole on plantar pressure. The footwear was prepared in three sizes: 22.5, 24.0 and 25.5 cm. Plantar pressure and gait parameters were measured during usual normal walking on a 20-m walkway. Before data collection, subjects practiced once on the same walkway to facilitate reproduction of their typical gait.

C. Variables

1) Plantar Pressure

The analyzed plantar pressure of toes and forefoot variables included mean peak pressure (MPP) and pressure–time integral (PTI). After the initial three steps and final three steps were removed, the plantar pressure variables were calculated using the mean value of all steps (approximately 15–22 steps) per subject. Plantar pressure distribution in the stance phase was divided according to the four segments [8] (Figure 3). This study focuses on the plantar pressure of the toes and forefoot. In this study, both left and right feet values were used as the plantar pressure variables in analysis.

2) Gait Features

The gait features investigated in this study included amplitude of motion. The amplitude of motion was divided into three phases of the gait cycle (TABLE 1), and the mean values were calculated using the maximum values across steps per subject. The ML width of centre of pressure (COP) excursion of the foot depends mainly on the inversion/eversion movements made to improve landing control, energy storage and propulsion [12]. The AP length of COP excursion indicated the ability of push-off using the toes.

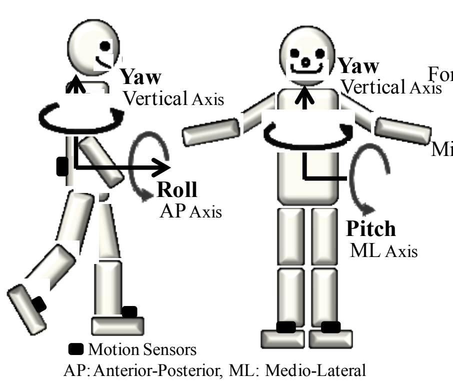

Figure 2. Three–dimensional axes

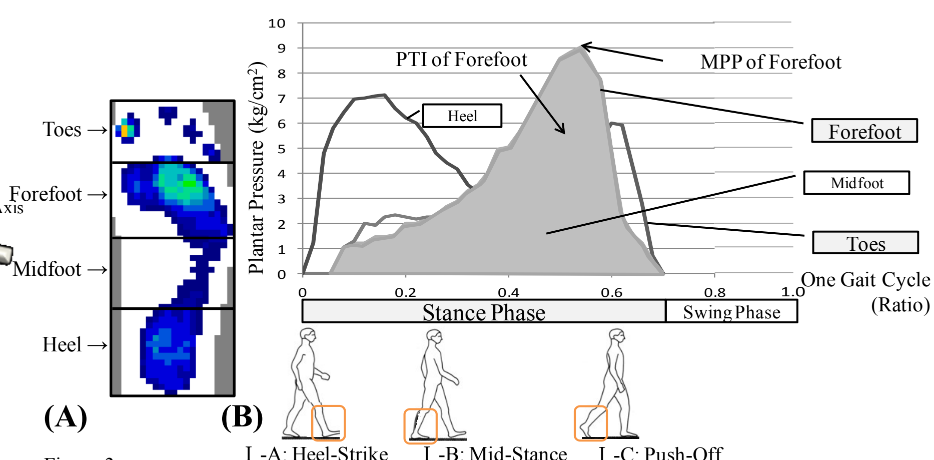

Figure 3.
(A) Plantar pressure distribution image was divided into four segments
(B) Plantar pressure and phase of gait cycle

D. Data Analysis

Descriptive data were expressed as mean ± standard deviation for continuous variables and n (%) for categorical variables. Incidentally, what is high plantar pressure? Some studies have identified cut-off values for accurate prediction of the risk of diabetic foot ulcer in diabetic patients with increased plantar pressure. However, no cut-off values have been distinguished for each segment of the plantar, despite differences in these segments, as shown in a previous study [8]. Thus, plantar pressure in diabetic patients must be compared to that of the non-diabetic subjects to distinguish elevated plantar pressure and whether it is different for segments of the plantar. Thus, elevated plantar pressure was distinguished by more than the mean + one standard deviation of the corresponding segments in nondiabetic subjects. First, characteristics were compared between the diabetic patients and matched non-diabetic subjects using Student's t-test, Chi-square test and Fisher's exact test. Gait features were compared between the foot with elevated plantar pressure and the one with normal plantar pressure. These variables were used for stepwise logistic regression analysis when the p-value was <0.1. When multicollinearity among the independent variables was observed (r > 0.60), only one of the variables was entered into the model. Finally, the gait features relevant to elevated plantar pressure in diabetic patients were compared with nondiabetic subjects by t-test. The statistical significance level was set at p = 0.05. All data processing and statistical analyses were conducted using MATLAB R2012a (The Math Works, Inc., MA, USA).

TABLE 2. Characteristics of the Subjects

	Nondiabetic Subjects n=49	Diabetic Patients n=57	p-value	
Age (y)	66.0±10.9	66.6±10.8	0.787	1)
Sex				
Male	29 (59.2)	36 (63.2)	0.675	2)
Female	20 (40.8)	21 (36.8)		
Height (m)	1.62±0.09	1.63±0.08	0.482	1)
BMI				
<18.5	3 (6.1)	4 (7.0)	0.329	3)
18.5-25.0	35 (71.4)	33 (57.9)		
>25.0	11 (22.5)	20 (35.1)		
Motor Neuropathy	13 (26.5)	33 (57.9)	0.001	*2)
Sensory Neuropathy	8 (16.3)	32 (56.1)	<0.001	*2)
Angiopathy	0 (0.0)	4 (7.0)	0.059	3)
One Gait Cycle (s)	1.07±0.12	1.08±0.08	0.391	1)
Stance Phase (s)	0.66±0.09	0.68±0.06	0.260	1)
Type of Diabetes				
Type1	-	4 (7.0)	-	
Type2	-	50 (87.7)	-	
Other	-	3 (5.3)	-	
HbA1c (NGSP) (%)	-	7.0±1.2	-	
Diabetes Duration (y)	-	14.4±10.6	-	
History of Diabetic Foot Ulcer	-	2 (3.5)	-	

mean±SD, n (%) * p<0.05 1) t-Test, 2)Chi-Square Test, 3)Fisher's Exact Test
NGSP: National Glycohemoglobin Standardization Program

III. RESULTS

Sixty-eight diabetic patients were encountered at the Diabetic Foot Outpatient Clinic during the observation period. Nine patients were excluded because they used a walking stick or wheel–chair (n = 2), had a current diabetic foot ulcer (n = 1), 4). Inability to provide consent for participation (n = 1), difficulty wearing the required footwear (n = 1) and missing data (n = 2) were other reasons for exclusions. Therefore, data for 57 patients were included in the analyses. Forty-nine age- and sex-matched nondiabetic subjects were selected.

TABLE 3. Relationship between Elevated Plantar Pressure and Gait Features in Diabetic Patients

Plantar Pressure	Gait Features [Ⅰ: Heel-Strike, Ⅱ: Mid-Stance, Ⅲ: Push-Off]			LO	OR	95%CI	p-value
Toes MPP	Ⅲ	Foot	COP Excursion Length (AP Axis) (Adjusted Foot Length)	0.149	1.16	1.07 - 1.26	<0.001
Toes PTI	Ⅱ	Body	Roll Angle (AP Axis)	-1.244	0.29	0.13 - 0.65	0.002
	Ⅲ	Foot	COP Excursion Length (AP Axis) (Adjusted Foot Length)	0.721	2.06	1.41 - 3.00	<0.001
Forefoot MPP	Ⅰ	Body	Pitch Angle (ML Axis)	0.780	2.18	0.99 - 1.00	0.012
	Ⅱ	Body	Roll Angle (AP Axis)	-0.008	0.99	1.18 - 4.03	0.016
	Ⅱ	Feet	Yaw AngVelo (Vertical Axis)	-0.952	0.39	0.17 - 0.86	0.019
Forefoot PTI	Ⅰ	Body	Pitch AngVelo (ML Axis)	0.027	1.03	1.00 - 1.05	0.033

Logistic Regression Analysis, Stepwise Selection n=114 (57×2)
LO: Log Odds, OR: Odds Ratio, CI: Confidence Interval

TABLE 4. Gait Features Relevant to Elevated Plantar Pressure in Diabetic Patients Compared with Nondiabetic Subjects

Gait Features			Nondiabetic Subjects (n=49×2)	Diabetic Patients (n=57×2)	p-value
Ⅰ: Heel-Strike	Body	Pitch Angle (ML Axis)	0.95±0.61	1.11± 0.77	0.094
	Body	Pitch AngVelo (ML Axis)	33.56±13.42	36.45±15.71	0.155
Ⅱ: Mid-Stance	Body	Roll Angle (AP Axis)	1.55±1.14	1.42±0.96	0.354
	Feet	Yaw AngVelo (Vertical Axis)	384.42±124.79	334.28±103.10	0.002*
Ⅲ: Push-Off	Foot	COP Excursion Length (AP Axis) (Adjusted Foot Length)	0.79±0.07	0.77±0.07	0.031*

t-test, *p<0.05

Characteristics of these subjects are detailed in TABLE 2. No significant differences in age, sex, BMI or one gait cycle were found.

The mean ± SD value of toes MPP was 3.45±1.55kgf・cm^2, toes PTI was 6.85±5.12kgf・s, forefoot MPP was 3.84±1.32kgf・cm^2 and forefoot PTI was 33.24±14.46kgf・s in diabetic subjects. The mean + one standard deviation of toes MPP was 4.62kgf・cm^2, toes PTI was 8.27kgf・s, forefoot MPP was 4.78kgf・cm^2 and forefoot PTI was 33.15kgf・s in nondiabetic subjects. Thirty feet in toes MPP, 29 feet in toes PTI, 27 feet in forefoot MPP and 42 feet in forefoot PTI were distinguished to have elevated plantar pressure.

Some gait features were relevant to the elevated plantar pressure in diabetic patients (TABLE 3). Toes MPP and PTI reflected motion in the push-off phase (Ⅲ), forefoot MPP and PTI reflected motion in the mid-stance phase (Ⅱ), as expected. The long AP length of COP excursion means pressure was applied until motion reached the toes. Thus, toes plantar pressure was elevated if the subjects could do push-off of the toes. Unexpectedly, toes PTI was also relevant to mid-stance phase (Ⅱ), and forefoot MPP was relevant to heel-strike phase (Ⅰ). These results suggest the complexity of gait in diabetic patients. All gait features of heel-strike phase (Ⅰ) and push-off phase (Ⅲ) were positively correlated with elevated plantar pressure.

Almost motion of mid-stance and push-off in diabetic patients were significantly smaller than nondiabetic subjects. By contrast, motion of heel-strike in diabetic patients was slightly larger than nondiabetic subjects (TABLE 4).

IV. Discussion

This is the first report to reveal what kind of gait feature was relevant to pressure-elevated segment and its plantar pressure raise in diabetic patients. It was newly revealed that some of gait features were relevant to the elevated plantar pressure in the diabetic patients. Especially, small rolling during the mid-stance phase was relevant to elevated plantar pressure.

It was revealed that the diabetic patients who had elevated plantar pressure had motion of small rolling during the mid-stance phase (Ⅱ). During walking, the foot performs a rolling motion in which the plantar rolls over the ground during the mid-stance phase. The gait features of rolling are considered that distribute the plantar pressure by mainly inversion motion. If this motion was small, a small area of the plantar receives highly concentrated plantar pressure.

It was clarified that almost motion of mid-stance and push-off in diabetic patients were significantly smaller than nondiabetic subjects. It was reported that diabetic patients has higher plantar pressure compared with nondiabetic subjects, thus higher plantar pressure may have been found associated with gait features at the timing of the push-off and a mid-stance. Motion of heel-strike in diabetic patients was slightly larger than nondiabetic subjects, it may be compensatory motion in diabetic patients. The compensatory motion might appear in this gait cycle, since the heel strike motion is considered to be easy to control compared with other motion.

In clinical settings, increasing the motion of mid-stance may prevent elevated plantar pressure in diabetic patients. For instance, passive exercise is recommended for expansion of ankle ROM. In addition, increasing muscle strength of the lower limbs may be effective.

The diabetic patients in this study may have been at lower risk patients for foot ulcers, since most patients were classified as grade 0 or 1 according to the classification of the International Working Group on the Diabetic Foot [13]. However, the findings of this study may be valuable in prevention of foot ulcers at an early stage of diabetes. Future studies are necessary to confirm these findings in higher-risk patients.

V. Conclusion

This is the first report to reveal what kind of gait feature was related to pressure-elevated segment and its plantar pressure raise in diabetic patients. To conduct this study, a simultaneous measurement system of plantar pressure and gait features was constructed. Elevated plantar pressure in diabetic patients and its relationship with their gait features were revealed. Small rolling during the mid-stance phase was relevant to elevated plantar pressure of toes and forefoot.

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